Tomography of Integrated Circuit Interconnects

The power of the x-ray tomographic technique in three dimensions is demonstrated through the reconstruction of images of integrated circuit interconnects. A two-layer interconnect is imaged with a Fresnel zone plate with a Raleigh resolution of 120 nm, and a region of an electromigration void is imaged with a Fresnel zone plate with a resolution of 55 nm. Results from the use of a Bayesian method for reconstruction are presented.

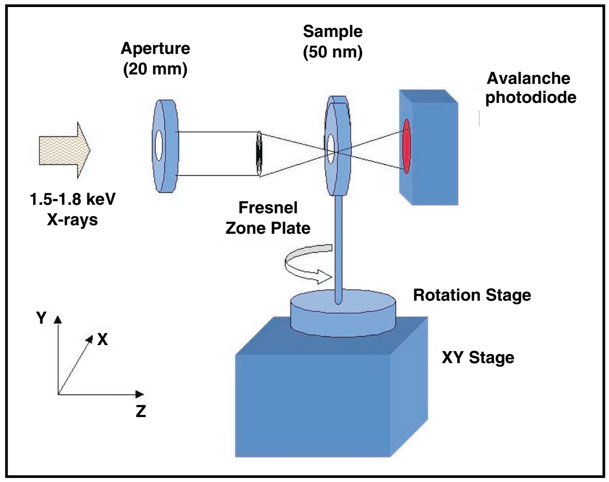

FIG. 1. Schematic of a scanning transmission x-ray microscope.

The modern era of x-ray tomography began around 1960 with a modest measurement of two metal cylinders at a resolution of 7 mm. Within two decades, computerized axial tomography scanners were a major new diagnostic tool in medicine. Resolution improved gradually; however, in medicine it is necessary to limit the dose to the patient, which limits the resolution. The constraint on dosage is relaxed by orders of magnitude for inorganic samples. This insight launched synchrotron-based microtomography in 1987 [1], with a resolution of 15 μm, improving to 3 μm by 1992 [2]. The use of Fresnel zone plates permitted a dramatic improvement in resolution in synchrotron-based x-ray tomography [3]. A test pattern of gold bars on a silicon nitride window was imaged with a resolution of 50 nm. A similar resolution was achieved in a biological sample in 1997 [4].

We have performed tomographic reconstructions of integrated circuit interconnects. Integrated circuit interconnects are three-dimensional structures of considerable complexity. Three-dimensional images of integrated circuits are of potential interest to both process development and failure analysis groups within the semiconductor industry. X-ray tomography offers three-dimensional imaging with better resolution than optical microscopy, as well as the ability to view optically hidden structures, and it is less invasive than the thinning required for transmission electron microscopy.

We achieved 400-nm resolution in the initial experiment [5] which improved to 140 nm more recently [6]. Our technique involved using scanning transmission x-ray tomography at beamline 2-ID-B of the Advanced Photon Source [7]. A schematic of the experiment is shown in Fig. 1. Monochromatic light from the beamline is focused onto a sample using a Fresnel zone plate. The intensity of the transmitted x-rays is recorded with a single-channel avalanche photodectector. The sample is rastered through the beam. Images are acquired at several angles.

The scanned images must be aligned; moreover, they suffered a linear distortion due to a lack of ideality in the motion of the scan stage. Special techniques were developed that were specific to the problem of aligning integrated circuit interconnects [8,9]. In particular, the wiring directions in the sample are engineered to be orthogonal to a high degree of accuracy. An analysis of the two-dimensional projections (i.e., the scanned images) allowed a fit of a

6-parameter model that yielded 3 parameters describing the orientation of the sample relative to the laboratory coordinates (parameters equivalent to Euler angles) and 3 additional parameters describing linear distortion (other than overall scale) of the actual motion of the scanning stage relative to nominal coordinates. By considering the Radon transform of the images, it was possible to automate the identification of the location and orientation of wire edges and improve the accuracy of such identification by a factor of four [9].

We considered two algorithms for the tomographic analysis: the simultaneous iterative reconstruction technique (SIRT) [10] and a Bayesian method called the generalized Gaussian Markov random field (GGMRF) method [11]. In practice, the image reconstruction problem is underconstrained because we have several times more degrees of freedom in the image than the number of observations. Hence, it is necessary to make assumptions. The SIRT algorithm makes assumptions about the unconstrained data implicitly: it never modifies any linear combination of the data that does not affect a constraint equation [12]. If one starts, as we do, from an initial guess of 0, this approach is equivalent to assuming a 0 value for the missing data.

Under a Bayesian method, the reconstructed image depends upon both the measured data and explicit assumptions about the missing data. Bouman and Sauer introduced the GGMRF method in part to handle abrupt changes in density in materials inspection problems in tomography, while retaining much of the analytic simplicity of the earlier Gaussian Markov random field (GMRF) method. The materials inspection problem is characterized by the presence of a few edges, i.e., discontinuous changes in the density of the material.

The discontinuous changes tend to be blurred or noisy under GMRF but better reconstructed under the GGMRF, which does not penalize them as severely [11]. GMRF does well when the density to be reconstructed varies continuously.

Results of Bayesian reconstructions are shown in Figs. 2 and 3. The first is a two-layer interconnect imaged with a Fresnel zone plate with a Raleigh res-

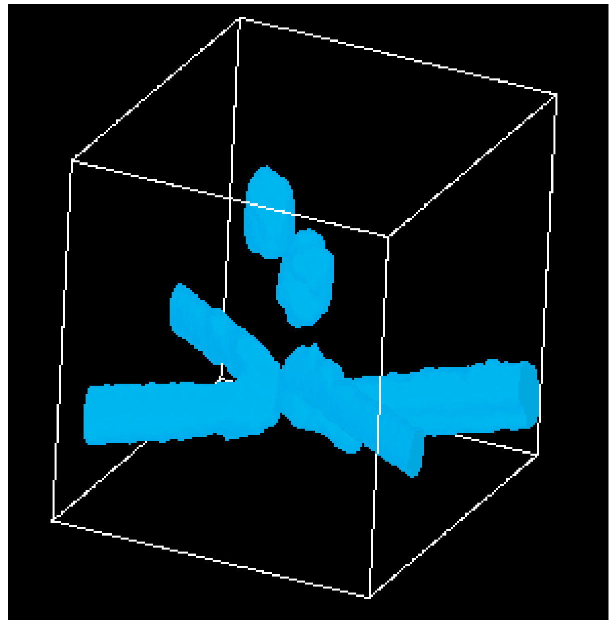

FIG. 2. Integrated circuit interconnect (courtesy Digital Equip- ment Corporation). The two wiring levels are 1.2 μm, center to center. The objects apparently floating above the circuit are focused ion beam markers. A VRML version of the SIRT reconstruction appears in Ref. 13.

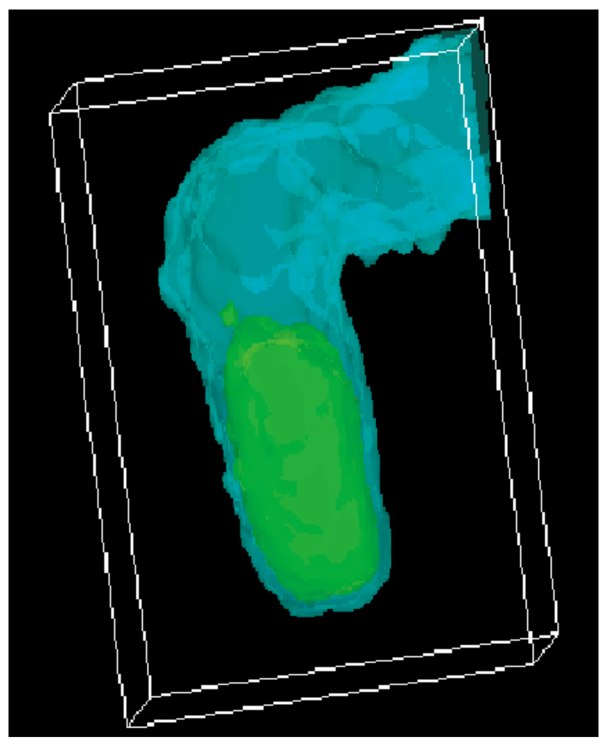

FIG. 3. Integrated circuit interconnect with an electromigration void (courtesy Digital Equipment Corporation). An individual via is shown connected to the wiring level above. The wire below has been swept away by electromigration. The green region (about 1 μm high) is primarily tungsten; the orthogonal wire is aluminum.

olution of 120 nm; the second is a region of an electromigration void imaged with a Fresnel zone plate with a resolution of 55 nm.

Looking to the future, the key issue for synchrotron work is the reduction of the scan times through direct imaging techniques. One may attempt to achieve a purely incoherent beam—as implemented first in Göttingen—or one may use phase retrieval techniques with a highly coherent beam. For industrial applications, it is necessary to bring the technology inside the factory. X-Radia, a company founded in part by former employees of Argonne National Laboratories, is dedicated to this mission. (Identification of a commercial entity does not imply recommendation nor endorsement.)

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This summary was written by Z.H. Levine.

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